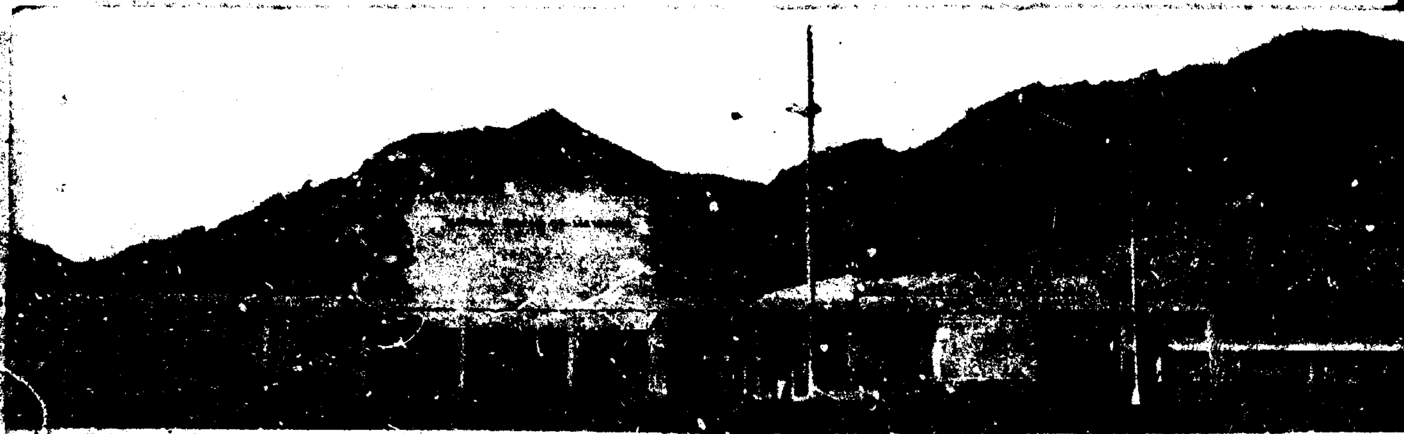

NBS REPORT

8812

A COMPILATION OF THE PROPERTY DIFFERENCES OF ORTHO AND PARA HYDROGEN OR MIXTURES OF ORTHO AND PARA HYDROGEN

J. G. Hust and R. B. Stewart

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) $2.00

Microfiche (MF) $.50

ff 653 July 65

NBS

N66 13084 (ACCESSION NUMBER)

40 (PAGES)

CR 68456 (NASA CR OR TMX OR AD NUMBER)

(THRU)

1 (CODE)

06 (CATEGORY)

FACILITY FORM 602

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
BOULDER LABORATORIES
Boulder, Colorado

NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT | **NBS REPORT**

31502-40-3150420 May 20, 1965 8812
31502-40-3150400

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by

J. G. Hust and R. B. Stewart

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

CONTENTS

	Page
ABSTRACT	1
1.0 INTRODUCTION	1
2.0 FORMAT	3
3.0 DATA SHEETS	3

A COMPILATION OF THE PROPERTY DIFFERENCES OF ORTHO AND PARA HYDROGEN OR MIXTURES OF ORTHO AND PARA HYDROGEN*

J. G. Hust and R. B. Stewart

The experimental property differences of ortho and para hydrogen and their mixtures as reported in the world literature for temperatures below 300°K are tabulated. Properties included are specific heat, velocity of sound, thermal conductivity, density, viscosity, vapor pressure, saturated liquid and saturated vapor densities, and latent heat of vaporization. Pertinent comments regarding the experimental methods employed, the pressure and temperature range of the data, and the accuracy of the data are included when available.

1.0 INTRODUCTION

This compilation presents the results of a literature search for ortho and para hydrogen property differences up to 300°K. The literature file of the Documentation Unit of the Cryogenic Data Center was searched and approximately 900 references containing ortho and para hydrogen data were obtained. These in turn were searched for additional documents containing experimental data. The objective was to obtain thermophysical property data which could be used to determine the differences in these properties for any mixture of the ortho and para modifications of hydrogen.

The hydrogen properties can be separated into two groups; the first group of properties exhibits relatively large changes in value, while the second group of properties exhibits very small changes in value, with differences in ortho-para composition. The properties with significant ortho-para dependency include specific heat and properties related to specific heat, such as velocity of sound, entropy, enthalpy, and thermal conductivity. The properties which are almost independent of ortho-para concentrations include density and viscosity. Information is also included on the vapor pressures, densities of saturated liquid and saturated vapor, and on latent heat of vaporization for normal and para hydrogen.

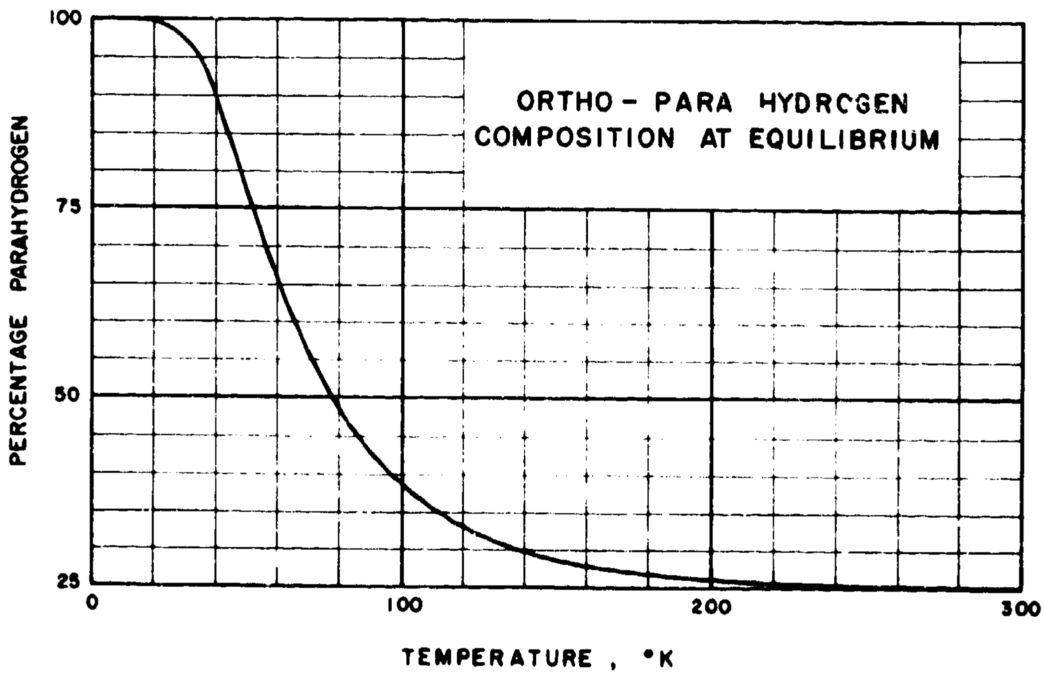
Property value differences due to ortho-para composition of hydrogen for specific heats, velocity of sound, entropy, enthalpy, and thermal conductivity, from about 50° to 300°K are significantly larger than the experimental errors in their measurement. Therefore, data of various ortho-para mixtures, from different sources which may not have the same systematic experimental errors, may be compared in temperature ranges where these large differences occur, to ascertain the variation of the property as a function of ortho-para concentration. For this group of properties, selected data from the literature are listed from which these differences may be obtained.

Property value differences due to ortho-para composition for density and viscosity may be expected to be of the same order of magnitude as the systematic experimental errors in their measurements. Therefore, independent alternate sets of data for a given property of different ortho-para composition cannot generally be regarded as a sufficient measure of property differences due to ortho-para composition. For this reason, the data sources referenced in this report for this group of property data have been limited to (1) direct measurements of property differences due to ortho-para concentration (2) data sets of differing ortho-para composition which have been measured in the same laboratory and which may be regarded as having the same systematic errors, and (3) data which are regarded as having a probable uncertainty which is smaller than the differences in the property values.

*This compilation is a result of a study made under contract with the National Aeronautics and Space Administration.

The equilibrium concentration of ortho and para hydrogen in the ideal gas state has been calculated by Woolley, Scott, and Brickwedde (1948), J. Res. Natl. Bur. Std. 41, 379-475. The effect of pressure on these equilibrium concentrations is considered to be negligible. These values are tabulated and illustrated graphically below. The NBS-1939 Temperature Scale was used in this table.

Ortho-Para Composition at Equilibrium	
Temp. °K	Percentage in para form for H_2
10	99.9999
20	99.821
30	97.021
40	88.727
50	77.054
60	65.569
70	55.991
80	48.537
90	42.882
100	38.620
120	32.959
150	28.603
200	25.974
250	25.264
300	25.072



2.0 FORMAT

This report is a collection of independent data sheets on each of several properties for which information has been compiled. For each data sheet the following information is listed: Data Sources, Comments, and Data. All references containing data pertinent to this report are listed under Data Sources. The Comments Section includes a general summary for each property and in addition, pertinent comments about each reference. The type of experimental apparatus, indicated accuracy of results and range of data are included whenever available. The original data as tabulated in the data sources are listed in the Data Section. If sufficient data are available they are also illustrated graphically.

3.0 DATA SHEETS

		Page
3.1	ZERO PRESSURE PROPERTIES (IDEAL GAS)	5
3.2	SPECIFIC HEAT	11
3.3	THERMAL CONDUCTIVITY	13
3.4	VISCOSITY DATA	17
3.5	VELOCITY OF SOUND	21
3.6	P-V-T AND VIRIAL COEFFICIENT DATA	27
3.7	SATURATION DENSITIES	29
3.8	VAPOR PRESSURE	33
3.9	LATENT HEAT OF VAPORIZATION	39

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3.1 ZERO PRESSURE PROPERTIES (IDEAL GAS)

Data Sources:

Woolley, H. W., Scott, R. B., and Brickwedde, F. G. (1948), Compilation of Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modifications, J. Res. Natl. Bur. Std. 41, 379-475, RP-1932.

Haar, L., Friedman, A. S., and Beckett, C. W. (1961), Ideal Gas Thermodynamic Functions and Isotope Exchange Functions for Diatomic Hydrides, Deuterides, and Tritides, Natl. Bur. Std. Monograph No. 20, 271 p.

Comments:

Both Woolley, et al. (1948) and Haar, et al. (1961) have computed ideal gas thermal properties for normal and para hydrogen from 10°K to above 300°K. The values of Haar, et al. have been obtained with spectroscopic data as recent as August 1958. The ortho-para differences from these sources are the same. Therefore, only the values of Haar, et al. are listed. Values for orthohydrogen are also included by Woolley. These additional tables are not given here, however, ortho-para differences are illustrated graphically.

Ideal gas properties for mixtures other than those tabulated may be calculated by the following equations. The specific heat and enthalpy of a given constant mixture of ortho and para hydrogen are obtained by,

$$C_{P(mix)} = X_{(p)}\, C_{P(p)} + X_{(o)}\, C_{P(o)}$$

$$H_{(mix)} = X_{(p)}\, H_{(p)} + X_{(o)}\, H_{(o)}$$

where the subscripts (p) and (o) refer to para and ortho and X is the relative amount of each component present. The entropy of a mixture, however, is also dependent upon the entropy of mixing as follows:

$$S_{(mix)} = X_{(p)}\, S_{(p)} + X_{(o)}\, S_{(o)} - R\left[X_{(o)} \ln X_{(o)} + X_{(p)} \ln X_{(p)}\right]$$

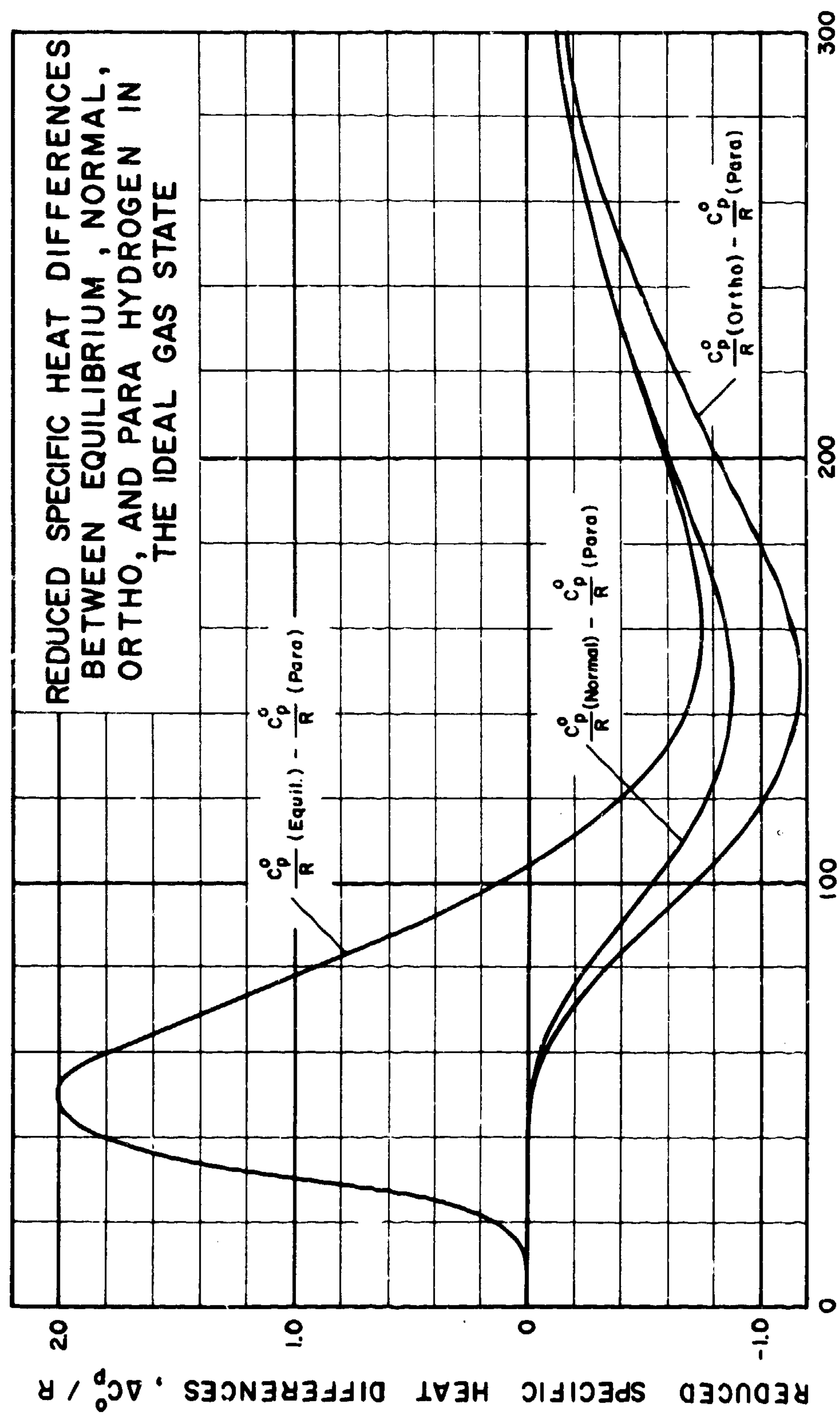
(Note that $X_{(p)} = 1 - X_{(o)}$ for a mixture of ortho and para hydrogen.) Since orthohydrogen properties are not tabulated here these equations are rewritten in terms of normal and para hydrogen properties as,

$$C_{P(mix)} = C_{P(p)}\left(X_{(p)} - \frac{X_{(o)}}{3}\right) + \frac{4}{3} X_{(o)}\, C_{P(n)}$$

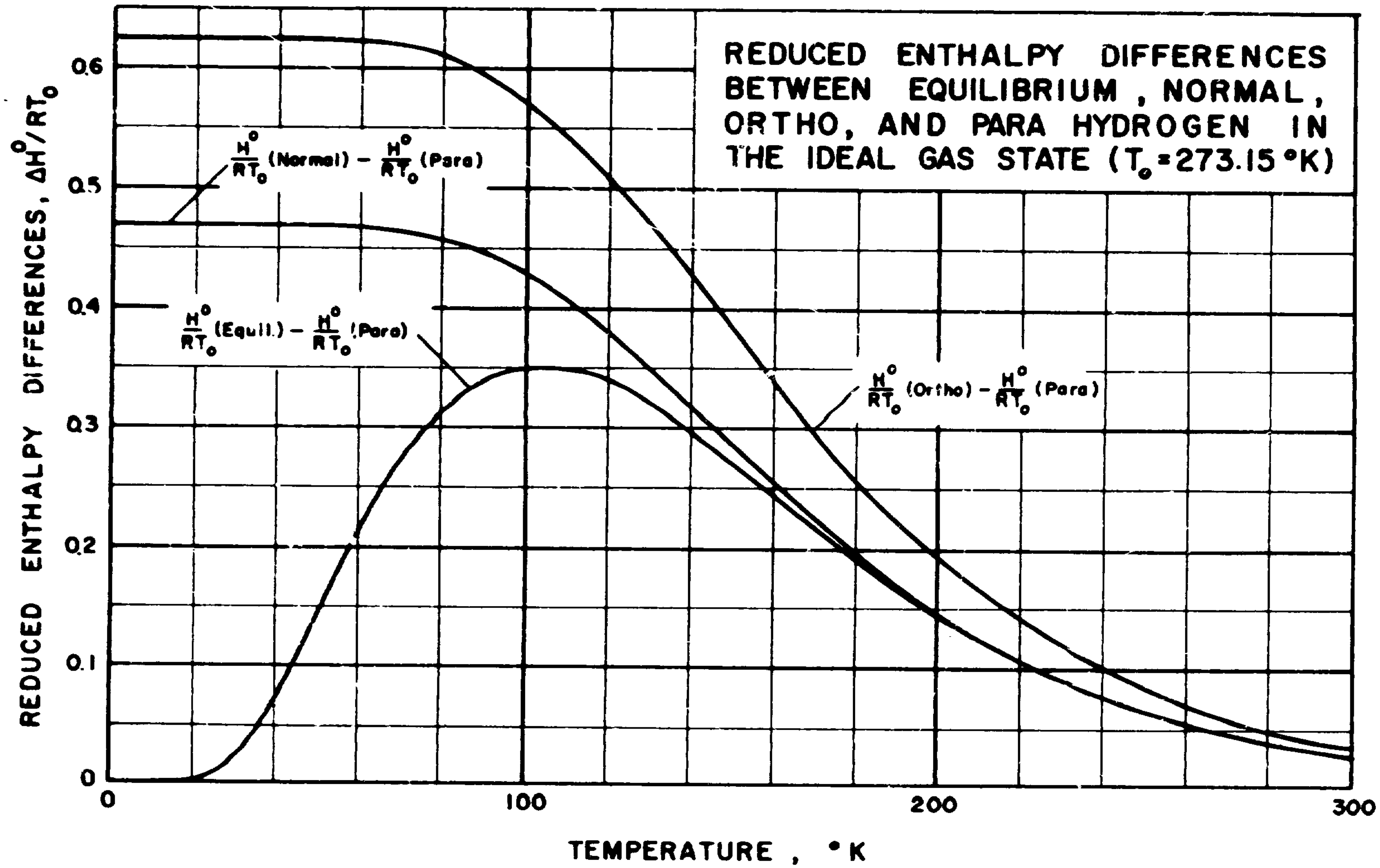
$$H_{(mix)} = H_{(p)}\left(X_{(p)} - \frac{X_{(o)}}{3}\right) + \frac{4}{3} X_{(o)}\, H_{(n)}$$

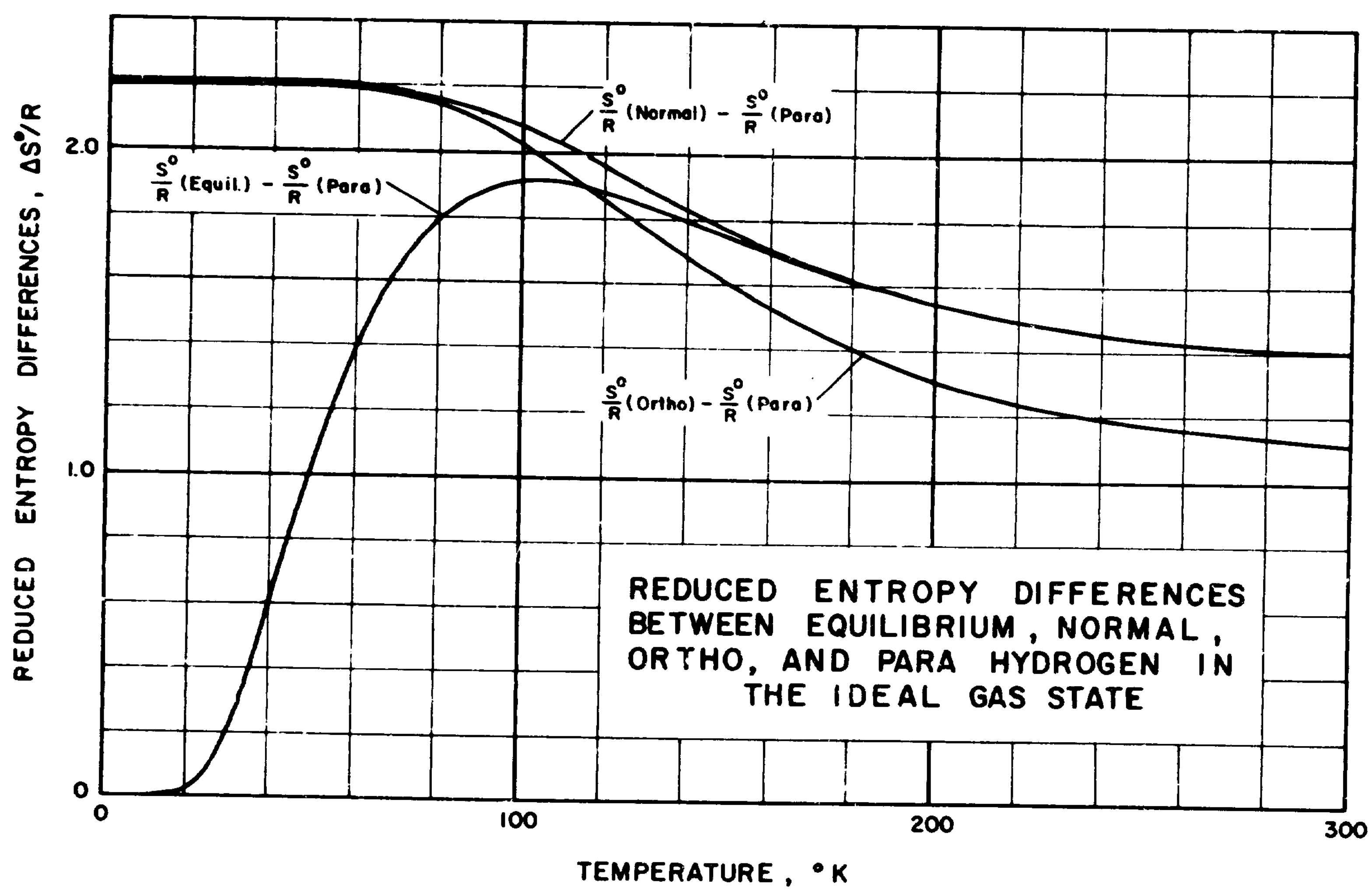
$$S_{(mix)} = S_{(p)}\left(X_{(p)} - \frac{X_{(o)}}{3}\right) + \frac{4}{3} X_{(o)}\left(S_{(n)} - R\, 0.562336\right) - R\left(X_{(o)} \ln X_{(o)} + X_{(p)} \ln X_{(p)}\right).$$

Haar, et al. (1961)									
Zero Pressure Properties									
Temp. °K	Specific Heat C_p°/R			Enthalpy $(H^\circ - E_0^\circ)/RT$			Entropy S°/R		
	Normal	Para	Equilibrium	Normal	Para	Equilibrium	Normal	Para	Equilibrium
10	2.50000	2.50000	2.50010	15.28092	2.50000	2.50001	6.46742	4.25717	4.25718
20	2.50000	2.50000	2.62977	8.89040	2.50000	2.51526	8.20027	5.99002	6.00707
30	2.50002	2.50006	3.43279	6.76031	2.50000	2.66925	9.21393	7.00368	7.20317
40	2.50059	2.50238	4.31745	5.69528	2.50019	2.98045	9.93317	7.72307	8.32294
50	2.50488	2.51943	4.56668	5.05666	2.50191	3.28362	10.49150	8.28283	9.32523
60	2.51868	2.57365	4.35857	4.63234	2.50868	3.48370	10.94922	8.74623	10.14337
70	2.54678	2.68123	4.03311	4.33221	2.52498	3.58552	11.33938	9.15032	10.79089
80	2.59041	2.84128	3.74645	4.11160	2.55403	3.62284	11.68214	9.51828	11.30997
90	2.64746	3.03790	3.53296	3.94564	2.59663	3.62404	11.99042	9.86402	11.73819
100	2.71388	3.24810	3.38559	3.81909	2.65125	3.60707	12.27274	10.19495	12.10227
110	2.78512	3.44947	3.28948	3.72183	2.71480	3.58223	12.53471	10.51411	12.42009
120	2.85715	3.62491	3.23131	3.64678	2.78356	3.55519	12.78014	10.82202	12.70359
130	2.92697	3.76456	3.20084	3.58875	2.85390	3.52895	13.01161	11.11793	12.96086
140	2.99268	3.86528	3.19034	3.54385	2.92277	3.50504	13.23096	11.40084	13.19758
150	3.05332	3.92900	3.19402	3.50916	2.98792	3.48412	13.43953	11.66988	13.41775
160	3.10860	3.96082	3.20742	3.48242	3.04789	3.46637	13.63837	11.92464	13.62428
170	3.15860	3.96715	3.22716	3.46193	3.10188	3.45169	13.82836	12.16505	13.81929
180	3.20360	3.95470	3.25062	3.44635	3.14968	3.43986	14.01019	12.39153	14.00440
190	3.24394	3.92931	3.27586	3.43465	3.19143	3.43056	14.18450	12.60472	14.18082
200	3.27998	3.89600	3.30144	3.42604	3.22751	3.42346	14.35183	12.80544	14.34950
210	3.31206	3.85865	3.32637	3.41986	3.25847	3.41825	14.51265	12.99464	14.51119
220	3.34048	3.82013	3.34995	3.41562	3.28487	3.41461	14.66740	13.17325	14.66648
230	3.36555	3.78243	3.37177	3.41291	3.30732	3.41228	14.81645	13.34222	14.81587
240	3.38754	3.74686	3.39161	3.41140	3.32637	3.41102	14.96015	13.50244	14.95980
250	3.40673	3.71419	3.40937	3.41084	3.34252	3.41060	15.09884	13.65472	15.09862
260	3.42339	3.68480	3.42510	3.41101	3.35624	3.41086	15.23279	13.79981	15.23265
270	3.43778	3.65977	3.43889	3.41174	3.36792	3.41165	15.36226	13.93838	15.36218
280	3.45016	3.63605	3.45086	3.41290	3.37789	3.41284	15.48751	14.07101	15.48745
290	3.46074	3.61642	3.46120	3.41437	3.38644	3.41434	15.60877	14.19825	15.60874
300	3.46977	3.59962	3.47006	3.41607	3.39382	3.41605	15.72626	14.32057	15.72624



REDUCED SPECIFIC HEAT DIFFERENCES BETWEEN EQUILIBRIUM, NORMAL, ORTHO, AND PARA HYDROGEN IN THE IDEAL GAS STATE
$\frac{C_p^o}{R}$ (Equil.) - $\frac{C_p^o}{R}$ (Para)
$\frac{C_p^o}{R}$ (Normal) - $\frac{C_p^o}{R}$ (Para)
$\frac{C_p^o}{R}$ (Ortho) - $\frac{C_p^o}{R}$ (Para)
2.0
1.0
0
-1.0
0
100
200
300
TEMPERATURE, °K
REDUCED SPECIFIC HEAT DIFFERENCES, ΔC_p^o / R


REDUCED ENTHALPY DIFFERENCES BETWEEN EQUILIBRIUM, NORMAL, ORTHO, AND PARA HYDROGEN IN THE IDEAL GAS STATE (T_o=273.15 °K)
$\frac{H^o}{RT_o}$(Normal) − $\frac{H^o}{RT_o}$(Para)
$\frac{H^o}{RT_o}$(Equil.) − $\frac{H^o}{RT_o}$(Para)
$\frac{H^o}{RT_o}$(Ortho) − $\frac{H^o}{RT_o}$(Para)
REDUCED ENTHALPY DIFFERENCES, $\Delta H^o/RT_o$
0
0.1
0.2
0.3
0.4
0.5
0.6
0
100
200
300
TEMPERATURE, °K



$\frac{S^0}{R}$ (Normal) − $\frac{S^0}{R}$ (Para)
$\frac{S^0}{R}$ (Equil.) − $\frac{S^0}{R}$ (Para)
$\frac{S^0}{R}$ (Ortho) − $\frac{S^0}{R}$ (Para)
REDUCED ENTROPY DIFFERENCES BETWEEN EQUILIBRIUM, NORMAL, ORTHO, AND PARA HYDROGEN IN THE IDEAL GAS STATE
REDUCED ENTROPY DIFFERENCES, $\Delta S^0/R$
2.0
1.0
0
0
100
200
300
TEMPERATURE, °K

3.2 SPECIFIC HEAT

Data Sources: See Comments

Comments:

The differences in the specific heat of ortho and para hydrogen, at low pressure, can be obtained by determining the allowed rotational energy states for these two molecular modifications. With increasing temperature, these differences become appreciable at 50°K, reach a maximum near 150°K, and decrease again, with only insignificant differences remaining at ambient temperatures. These values are tabulated in the Zero Pressure Properties Section (3.1) of this report. The low pressure differences in specific heat due to ortho-para concentration are good approximations for the high pressure differences since there are only slight differences in P-V-T behavior of ortho and para hydrogen. Several sources of data are available in which the pressure dependent part of the specific heat has been calculated from P-V-T relations, but since the small difference in the ortho-para hydrogen P-V-T surfaces is uncertain, little significance can be attached to the differences in specific heats that have been so obtained. Although the accuracy of the data is not sufficient for any conclusive determination, the available experimental specific heats confirm the postulate that the specific heat differences due to ortho-para concentration are essentially independent of pressure.

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3.3 THERMAL CONDUCTIVITY

Data Sources:

Farkas, A. (1935), Ortho-Para Hydrogen and Heavy Hydrogen, Cambridge University Press.

Ubbink. J. B. (1948), Thermal Conductivity of Gaseous Hydrogen and of Gaseous Deuterium, Physica 14, 165.

Powers, R. W., Mattox, R. W., and Johnston, H. L. (1954), Thermal Conductivity of Condensed Gases. II. The Thermal Conductivities of Liquid Normal and of Liquid Parahydrogen from 15 to 27°K, J. Am. Chem. Soc. 76, 5972-73.

Heinzinger, K. (1960), Die Wärmeleitfähigkeiten von Normal und Para - Wasserstoff bei 20°K. (The Heat Conductivity of Normal and Para Hydrogen at 20°K), Z. Naturforsch. 15a, 1022.

Heinzinger, K., Klemm, A., and Waldmann, L. (1961), Die Wärmeleitfähigkeit von Gasformigen Para-Ortho Wasserstoffgemischen bei 20°K. (The Thermal Conductivity of Gaseous Ortho-Para Hydrogen Mixtures at 20°K), Z. Naturforsch. 16a, 1338-42.

Comments:

Based upon the available experimental data it may be concluded that at liquid hydrogen temperatures the differences of thermal conductivity of ortho and para hydrogen are small. The differences for liquid hydrogen are less than 2%, while the differences for gaseous hydrogen near 20°K are about 0.5%.

Because of the large differences in low pressure specific heats of ortho and para hydrogen at intermediate temperatures, it is apparent that the thermal conductivities must also differ appreciably. These differences have apparently never become the object of experimental investigation. The ratio of the low pressure specific heats has, however, been calculated by Farkas (1935). This data source still seems to be the best available. The ratio of para to normal thermal conductivity as tabulated here was calculated, as indicated by Farkas using zero pressure specific heats by Haar, et al. (1961) [See Section 3.1].

$$\frac{K_p}{K_n} = \frac{C_{vp} + 2.25R}{C_{vn} + 2.25R}$$

Ubbink (1948) measured the thermal conductivity of gaseous hydrogen at temperatures ranging from 14 to 273°K. At 17°K he measured the thermal conductivities of para and normal hydrogen but could not detect any differences.

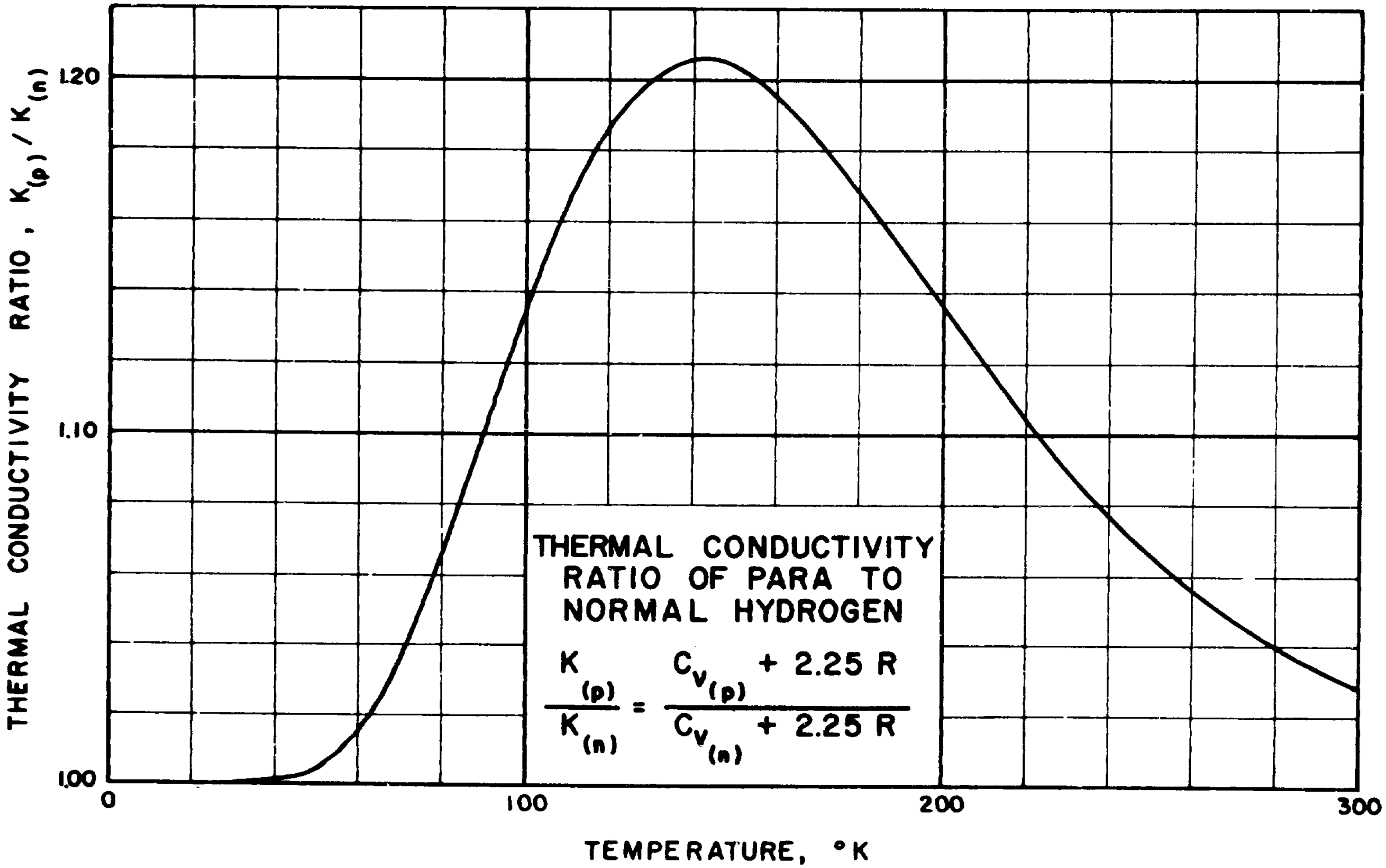
Powers, et al. (1954) used a parallel plate cell to measure the thermal conductivity of liquid normal and para hydrogen. Within their estimate of a probable error of 2%, no differences between normal and para hydrogen were observed. These results were represented by Powers, et al. by $K = (1.702 + 0.05573T)10^{-4}$ cal/(cm sec °K), with a rms deviation of 1.6%.

Heinzinger (1960) experimentally determined the thermal conductivity of gaseous parahydrogen to be 0.57±0.07% higher than normal hydrogen at 20°K. A year later Heinzinger, et al. (1961) reported measured values of thermal conductivity differences as a function of ortho-para hydrogen composition at 20°K.

Calculated Values of the Ratio of Thermal Conductivity of Gaseous Para to Normal Hydrogen, using the Equation by Farkas (1935)			
T, °K	K_p/K_n	T, °K	K_p/K_n
10	1.000	160	1.196
20	1.000	170	1.183
30	1.000	180	1.169
40	1.001	190	1.152
50	1.004	200	1.136
60	1.015	210	1.120
70	1.035	220	1.104
80	1.065	230	1.090
90	1.100	240	1.077
100	1.135	250	1.066
110	1.165	260	1.058
120	1.187	270	1.047
130	1.200	280	1.040
140	1.206	290	1.033
150	1.203	300	1.028

Powers, et al. (1954)			
Liquid Normal Hydrogen		Liquid Parahydrogen	
Temp. °K	Thermal Conductivity cal/(cm sec°K)	Temp. °K	Thermal Conductivity cal/(cm sec°K)
16.81	2.62×10^{-4}	16.83	2.81×10^{-4}
16.84	2.69	17.85	2.76
17.00	2.59	18.97	2.81
18.16	2.70	19.66	2.86
18.58	2.68	21.16	2.87
19.08	2.70	21.69	2.84
19.88	2.83	23.23	3.05
21.46	2.93		
22.72	2.94		
22.79	3.02		
23.84	3.02		
24.29	3.02		

Heinzinger, et al. (1961)	
(Gas at T = 20.5°K)	
Percent Parahydrogen	$(K - K_n)100/K_n$
100%	0.584%
86	0.540
70	0.404
61	0.363
53	0.315
50	0.250
47	0.203


THERMAL CONDUCTIVITY RATIO OF PARA TO NORMAL HYDROGEN
$\frac{K_{(p)}}{K_{(n)}} = \frac{C_{v_{(p)}} + 2.25\,R}{C_{v_{(n)}} + 2.25\,R}$
THERMAL CONDUCTIVITY RATIO, $K_{(p)}/K_{(n)}$
1.20
1.10
1.00
0
100
200
300
TEMPERATURE, °K

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3.4 VISCOSITY DATA

Data Sources:

Becker, E. W., and Stehl, O. (1952), Ein Zähigkeitsuntershied von Ortho- und Para-Wasserstoff bei Tiefen Temperaturen. (Viscosity Difference between Ortho and Para Hydrogen at Low Temperatures), Z. Physik 133, 615-28.

Webeler, R., and Bedard, F. (1961), Viscosity Difference Measurements for Normal and Para Liquid Hydrogen Mixtures, Phys. Fluids 4, 159-60.

Diller, D. E. (1965), Measurements of the Viscosity of Parahydrogen, J. Chem. Phys. 42, 2089-2100.

Comments:

The viscosity differences of gaseous ortho and para hydrogen determined by Becker and Stehl (1952) are small, approaching 1% near the triple point. Liquid values, however, differ by larger amounts with differences of about 5% at saturation near the triple point. Diller (1965) points out that the liquid differences are nearly zero when compared at the same densities rather than the same temperature. The results of Becker and Stehl (1952) indicate the viscosity of gaseous para hydrogen to be larger than gaseous normal hydrogen; while the results of Diller show the normal hydrogen values to be larger than the para hydrogen values in the liquid region.

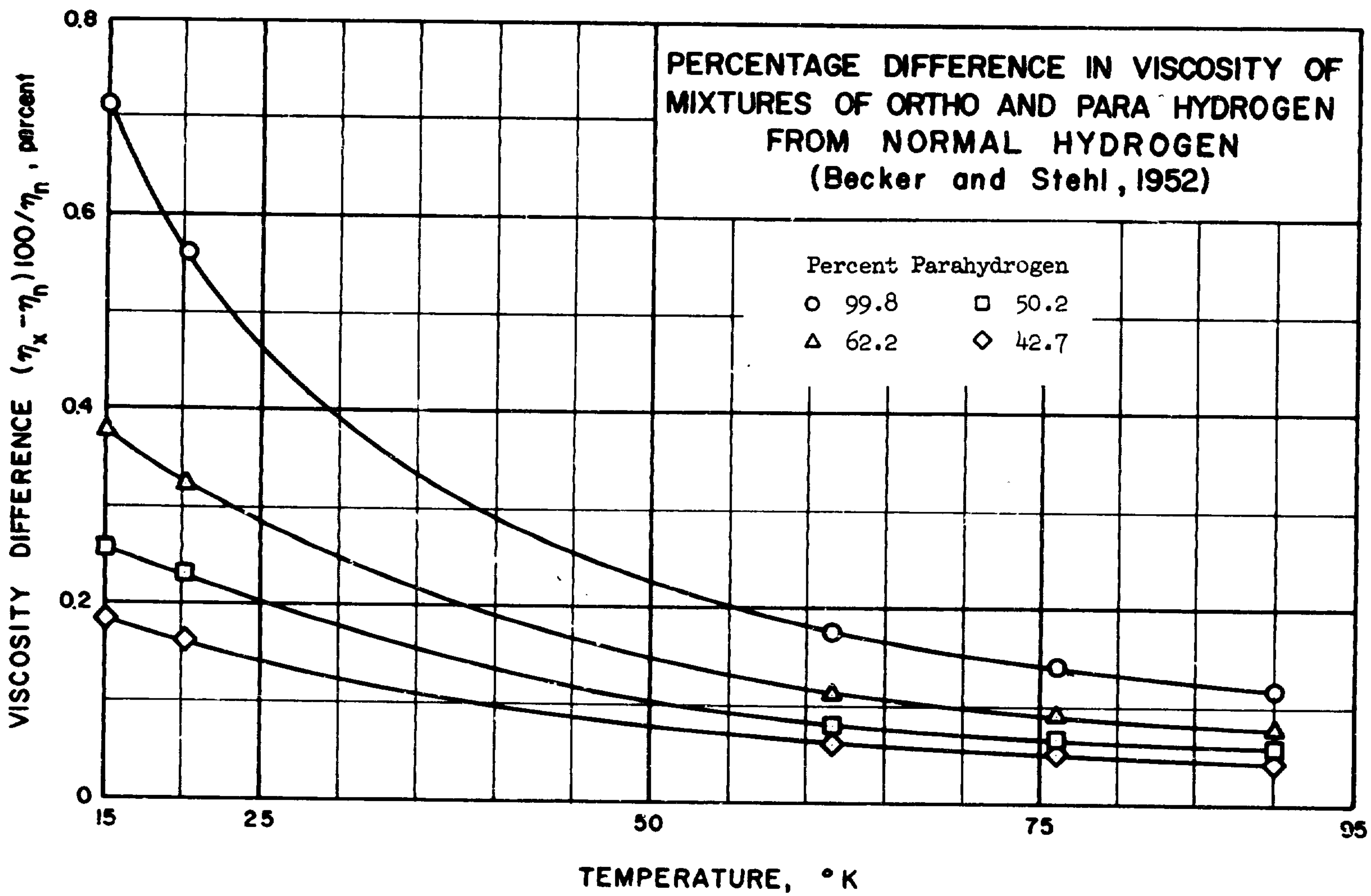
Becker and Stehl (1952) measured the difference in viscosity between various mixtures of ortho and para hydrogen with a capillary bridge arrangement.

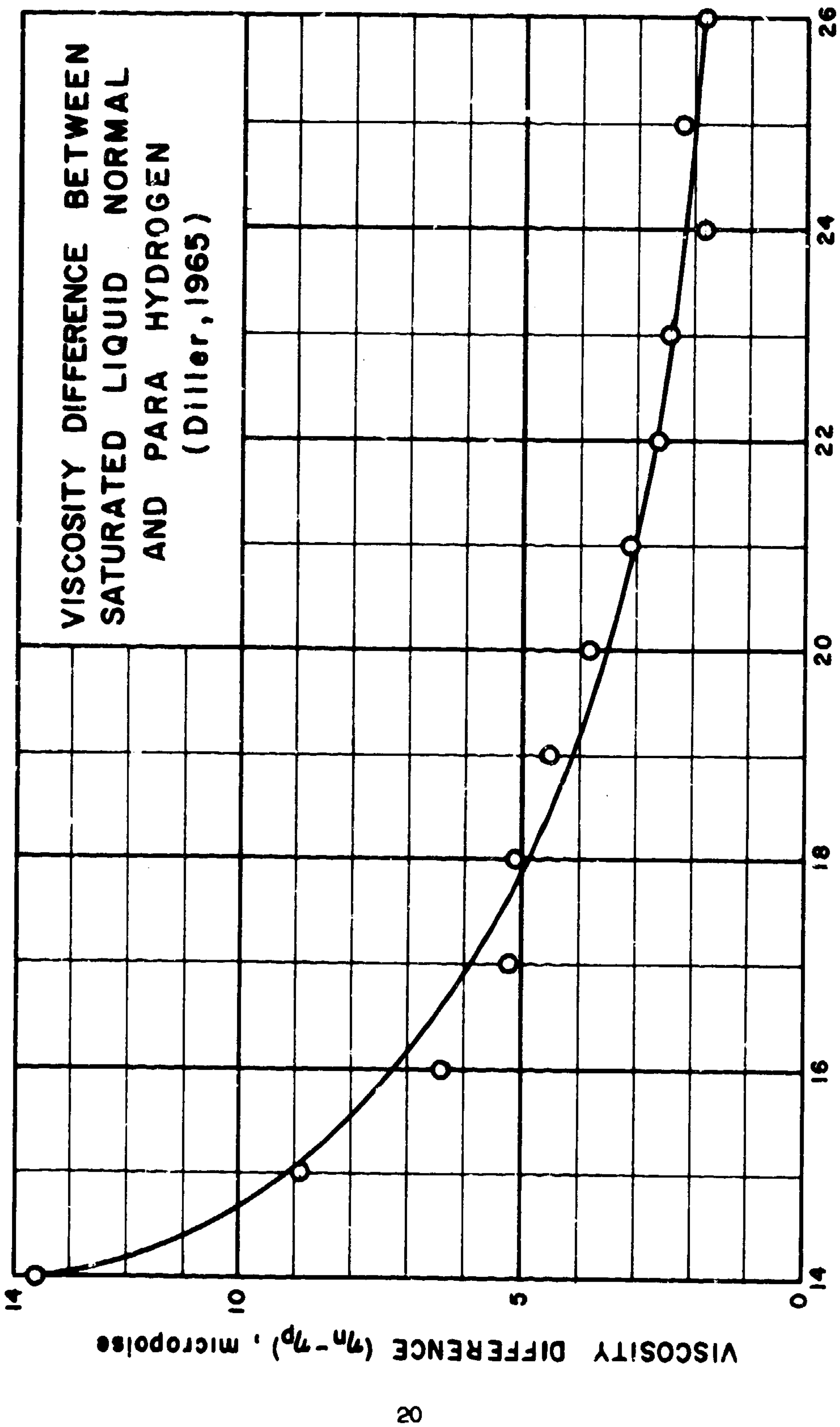
Webeler and Bedard (1961) measured a quantity equal to the product of viscosity and density of liquid para and ortho hydrogen with a piezoelectric alpha quartz torsional oscillator. They found that the value of $\eta\rho$ for 69% orthohydrogen at temperatures from 13.8 to 14.5 °K is about 4% larger than the corresponding values for 29% ortho hydrogen. The precision of the values of $\eta\rho$ is given as 0.2%.

Diller (1965) also used a torsional crystal method to make extensive measurements on para hydrogen. He included a few points for normal hydrogen along the saturated liquid line. All of the data are analytically represented with a mean deviation of 0.7%. An accuracy of 0.5% is claimed. The tables that follow include Diller's saturation data only.

Becker and Stehl (1952)				
Gaseous Hydrogen $(\eta_x - \eta_n)\ 100/\eta_n$				
T, °K	Percent Para Hydrogen			
	99.8	62.2	50.2	42.7
90.1	0.116	0.075	0.055	0.039
77.3	0.139	0.089	0.065	0.049
63.2	0.175	0.110	0.079	0.058
20.3	0.561	0.323	0.231	0.162
15.0	0.712	0.376	0.258	0.182
η_x = Viscosity of ortho-para hydrogen mixture η_n = Viscosity of normal hydrogen				

Diller (1965)			
Viscosity of saturated liquid (Micropoise)			
T, °K	Normal	Para	Difference
14	264.3*	250.7	13.6
15	230.2	221.3	8.9
16	203.9	197.5	6.4
17	182.9	177.7	5.2
18	165.6	160.5	5.1
19	151.5	147.0	4.5
20	139.2	135.4	3.8
21	128.4	125.3	3.1
22	118.7	116.1	2.6
23	110.5	108.1	2.4
24	102.6	100.8	1.8
25	95.7	93.5	2.2
26	89.0	87.2	1.8
* This value has been corrected for a typographical error.			


PERCENTAGE DIFFERENCE IN VISCOSITY OF MIXTURES OF ORTHO AND PARA HYDROGEN FROM NORMAL HYDROGEN
(Becker and Stehl, 1952)
Percent Parahydrogen
○ 99.8
□ 50.2
△ 62.2
◇ 42.7
VISCOSITY DIFFERENCE $(\eta_x - \eta_n)100/\eta_n$, percent
0
0.2
0.4
0.6
0.8
15
25
50
75
95
TEMPERATURE, °K


VISCOSITY DIFFERENCE BETWEEN SATURATED LIQUID NORMAL AND PARA HYDROGEN (Diller, 1965)
TEMPERATURE, °K
14
16
18
20
22
24
26
VISCOSITY DIFFERENCE ($\eta_n - \eta_p$), micropoise
0
5
10
14

3. VELOCITY OF SOUND

Data Sources:

Van Itterbeek, A., Van Dael, W., and Cops, A. (1961), Velocity of Ultrasonic Waves in Liquid Normal and Para Hydrogen (14-20°K), Physica 27, 111-16.

Van Itterbeek, A., Van Dael, W., and Cops, A. (1963), The Velocity of Sound in Liquid Normal and Para Hydrogen as a Function of Pressure, Physica 29, 965-73.

Younglove, B. A. (1965), Ultrasonic Velocity in Fluid Parahydrogen, Manuscript submitted for publication.

Comments:

The velocity of sound of liquid normal and para hydrogen has been accurately determined by both Van Itterbeek, et al. (1961, 1963) and Younglove (1965) below 20°K. The agreement of these differences from these sources is excellent. The differences in the gaseous states are not, however, well known. One may estimate these differences from the thermodynamic relationship, $C^2 = \gamma(\partial P/\partial \rho)_T$ where C = velocity of sound, $\gamma = C_p/C_v$, and P, T, and ρ are pressure, temperature and density, respectively. It is known from P-V-T measurements that the values of $(\partial P/\partial \rho)_T$ of normal and para cannot be much different. Thus in regions where the differences in C_p/C_v are large such as around 150°K one can estimate the percentage difference in velocity of sound as one half the percentage difference in the specific heat ratio of normal and para hydrogen.

Van Itterbeek, et al. (1961) measured the velocity of sound in saturated liquid normal and para hydrogen at temperatures from 14 to 20.5°K using a variable length interferometer. Their data indicate the velocity of sound in normal hydrogen to be 8 m/sec greater than in para hydrogen at frequencies of 1, 2, and 5 mc/sec. They estimate the uncertainty at 0.2%.

Van Itterbeek, et al. (1963) extended the above work to pressures of 240 kg/cm². The difference between normal and para hydrogen at low pressures is less than in the previous article by the same authors.

Younglove (1965) made velocity of sound measurements on fluid para hydrogen with a pulsed sound technique. Measurements were made from 15 to 100°K and up to 350 atmospheres, and are claimed to be accurate to 0.05%.

Van Itterbeek, et al. (1961)

Velocity of Sound in Saturated Liquid Normal Hydrogen

0.996 mc/sec		1.945 mc/sec		4.904 mc/sec	
Temp. °K	Velocity of Sound m/sec	Temp. °K	Velocity of Sound m/sec	Temp. °K	Velocity of Sound m/sec
20.37	1120.7	20.42	1119.2	20.44	1119.4
19.97	1131.7	20.10	1128.6	19.08	1156.8
19.67	1140.3	19.85	1136.0	18.42	1171.6
19.37	1149.9	19.58	1142.6	18.04	1182.3
18.93	1159.7	19.32	1150.4	17.45	1194.5
18.61	1166.7	19.02	1157.4	17.04	1203.1
18.18	1176.9	18.70	1165.8	16.57	1214.7
17.72	1187.9	18.35	1173.9	15.98	1227.6
17.15	1200.3	17.95	1183.5	15.32	1240.2
16.61	1211.5	17.52	1193.2	15.23	1241.2
16.04	1224.3	17.50	1203.9	14.59	1254.3
15.15	1242.8	16.49	1214.9	14.13	1262.3
14.59	1254.4	15.92	1227.3		
14.13	1263.6	15.44	1237.4		
		14.89	1247.8		
		14.52	1255.0		
		14.11	1262.6		

Velocity of Sound in Saturated Liquid Para-Hydrogen

0.987 mc/sec		1.937 mc/sec		4.869 mc/sec	
Temp. °K	Velocity of Sound m/sec	Temp. °K	Velocity of Sound m/sec	Temp. °K	Velocity of Sound m/sec
20.36	1114.3	20.41	1110.9	20.40	1115.3
20.08	1122.5	19.91	1125.3	19.46	1137.9
19.77	1130.8	19.53	1134.8	18.92	1151.1
19.55	1136.9	19.06	1146.2	18.24	1168.1
19.29	1144.4	18.62	1157.9	17.66	1182.1
18.67	1154.6	18.13	1168.5	16.99	1196.9
18.48	1164.1	17.53	1183.1	16.52	1204.3
18.02	1175.4	16.91	1196.5	15.88	1220.5
17.52	1186.3	16.38	1208.7	15.33	1230.1
16.91	1200.1	15.76	1221.7	14.83	1240.7
16.20	1214.9	15.08	1234.3	14.38	1249.2
15.29	1232.5	14.63	1243.2		
14.06	1255.9	14.17	1250.8		
		20.40	1111.8		
		19.76	1128.2		
		19.43	1138.7		
		19.00	1149.0		
		18.55	1159.0		
		17.96	1174.3		
		17.43	1188.5		
		16.93	1199.6		
		16.32	1208.5		
		15.59	1225.4		
		14.85	1240.4		
		14.06	1253.6		

Van Itterbeek, et al. (1963)

Velocity of Sound in Liquid Hydrogen

T = 20.50°K				T = 19.17°K			
n-H_2		e-H_2		n-H_2		e-H_2	
P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec
236.0	1742.1	240.0	1748.6	177.5	1647.4	188.5	1667.6
230.0	1732.7	229.0	1729.3	170.3	1633.3	183.5	1658.4
220.3	1715.4	221.0	1714.9	160.9	1615.6	175.0	1642.4
210.4	1697.3	211.5	1698.7	150.5	1594.0	170.0	1631.8
200.9	1679.9	202.3	1680.5	139.7	1571.4	161.0	1614.4
190.6	1660.7	192.5	1663.1	130.0	1549.6	151.0	1593.7
180.5	1641.6	181.5	1641.3	120.3	1528.0	140.5	1571.4
170.6	1622.0	171.5	1622.5	110.0	1500.0	130.2	1549.6
160.2	1601.0	161.2	1601.1	100.3	1480.6	120.0	1526.1
150.6	1580.9	150.5	1578.6	90.8	1456.4	109.5	1502.3
141.2	1560.4	141.0	1558.4	80.5	1429.7	100.5	1479.5
130.8	1537.1	131.5	1537.6	70.00	1400.6	90.7	1455.3
120.7	1513.0	121.5	1513.6	60.50	1327.5	80.5	1428.4
110.6	1489.4	109.7	1485.2	50.50	1341.3	71.50	1403.2
100.7	1465.3	100.7	1463.1	40.50	1309.5	61.00	1372.6
90.5	1438.5	91.0	1437.1	29.20	1270.2	51.25	1342.4
80.7	1411.6	79.0	1404.7	21.60	1241.1	42.90	1314.6
70.50	1382.1	68.75	1374.5	12.95	1206.3	34.20	1285.0
61.05	1353.6	60.00	1347.6	6.25	1177.3	26.10	1254.9
50.85	1320.7	50.40	1315.7	1.70	1155.5	18.10	1224.1
41.15	1287.2	40.50	1281.6			10.30	1192.6
31.10	1250.0	30.75	1245.5			6.20	1173.2
23.00	1218.1	20.85	1205.4			2.05	1153.9
17.25	1193.4	12.05	1166.4			1.50	1151.3
11.80	1169.4	7.10	1142.3				
8.40	1152.6	2.75	1119.6				
4.95	1135.4	1.20	1111.5				
1.40	1117.5						
T = 18.25°K				**T = 16.74°K**			
n-H_2		e-H_2		n-H_2		e-H_2	
P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec
127.0	1575.3	146.4	1592.0	90.4	1486.6	85.0	1468.2
135 5	1571.9	137.0	1571.9	88.7	1481.2	78.0	1450.9
128.5	1555.7	129.0	1553.9	84.0	1469.4	63.90	1426.7
118.5	1535.1	118.5	1531.1	74.80	1446.0	60.25	1403.2
108.0	1510.9	108.5	1507.7	65.40	1420.9	50.75	1375.8
97.3	1485.3	99.5	1486.8	55.40	1393.2	41.40	1347.6
87.2	1459.3	90.0	1462.8	45.90	1365.4	31.50	1316.3
87.0	1459.3	79.5	1436.5	37.00	1338.0	21.35	1282.3
78.7	1437.7	70.40	1410.7	26.85	1305.6	13.10	1252.6
69.30	1411.2	60.50	1382.5	19.60	1280.5	8.30	1234.4
60.55	1387.4	50.50	1352.7	13.50	1259.1	2.60	1211.7
50.55	1357.3	40.70	1321.0	6.80	1233.8	1.40	1207.0
40.40	1325.1	30.60	1287.4	1.60	1212.9		
31.00	1294.4	20.45	1250.6				
22.20	1263.6	12.75	1221.2				
15.00	1235.9	6.60	1195.3				
8.30	1208.5	2.40	1177.4				
2.30	1183.3	1.50	1173.1				

Van Itterbeek, et al. (1963) (cont.)

Velocity of Sound in Liquid Hydrogen

T = 16.09°K			
n-H_2		e-H_2	
P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec
60.50	1416.5	65.40	1426.8
55.00	1402.4	60.50	1413.6
49.90	1387.7	55.45	1400.1
45.10	1373.7	50.30	1385.0
35.30	1344.5	40.60	1356.6
30.15	1328.4	35.60	1341.6
25.10	1312.6	30.60	1326.0
20.35	1296.2	25.35	1309.1
15.10	1278.4	20.70	1292.8
10.20	1261.6	15.60	1275.4
5.95	1245.3	10.60	1257.2
2.05	1230.4	5.50	1238.3
		2.05	1224.8

T = 15.35°K			
n-H_2		e-H_2	
P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec
20.55	1308.9	38.50	1360.7
17.50	1298.6	36.20	1353.9
14.90	1290.0	32.15	1341.5
12.50	1282.2	28.05	1329.1
7.40	1263.0	21.40	1308.2
5.45	1256.8	17.30	1293.9
3.95	1251.1	15.05	1286.4
2.10	1244.6	12.00	1276.1
1.40	1241.5	9.85	1268.7
		6.55	1256.7
		4.10	1247.3
		1.70	1238.2

T = 15.14°K			
n-H_2		e-H_2	
P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec
28.70	1338.9	29.70	1336.5
26.70	1332.3	26.90	1327.7
23.40	1322.7	23.10	1315.6
20.15	1313.0	20.10	1305.6
17.20	1302.2	17.00	1295.8
14.00	1291.7	14.05	1285.0
11.10	1281.3	11.25	1275.7
8.50	1272.3	8.90	1267.2
5.90	1263.2	6.15	1257.2
3.30	1255.1	3.00	1246.0
1.50	1247.1	0.25	1235.2

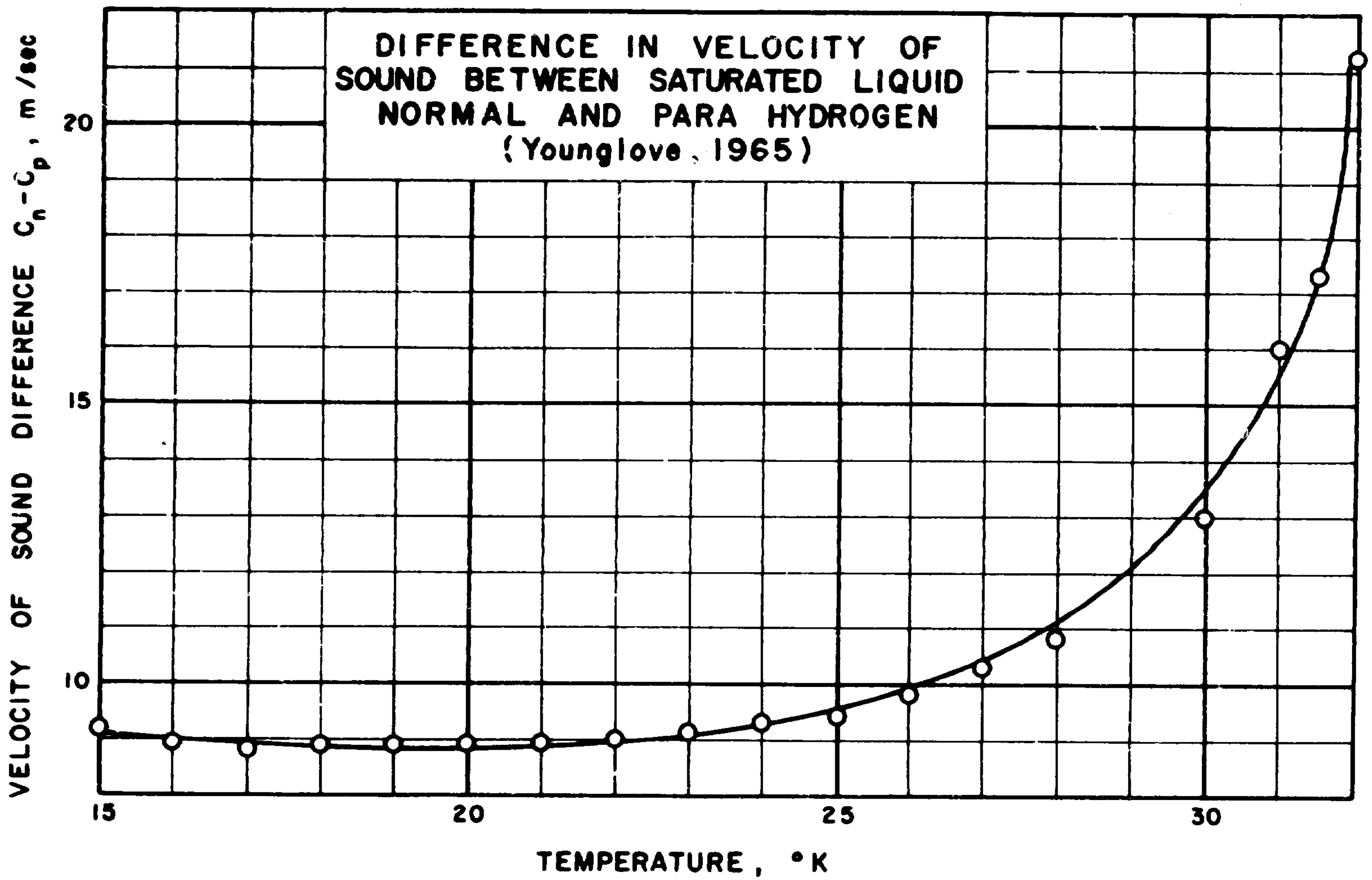
Younglove (1965)

Velocity of Sound in Saturated Liquid Hydrogen

T, °K	Density, g/cm³		Velocity of Sound, m/sec	
	Para	Normal	Para	Normal
14.5	0.07641		1241.9	
15	0.07599	0.07632	1232.6	1241.8
16	0.07510	0.07543	1212.8	1221.8
17	0.07417	0.07449	1191.7	1200.6
18	0.07319	0.07350	1169.0	1177.9
19	0.07216	0.07246	1144.6	1153.5
20	0.07108	0.07137	1118.5	1127.0
21	0.06992	0.07020	1090.3	1099.3
22	0.06870	0.06896	1060.0	1069.1
23	0.06739	0.06764	1027.3	1036.5
24	0.06599	0.06622	992.0	1001.3
25	0.06447	0.06469	953.6	963.1
26	0.06282	0.06302	911.8	921.7
27	0.06100	0.06120	866.0	876.3
28	0.05897	0.05917	815.2	826.1
29	0.05665	0.05687	758.2	770.0
29.5	0.05536	0.05559	726.6	739.0
30	0.05394	0.05420	692.6	705.6
30.5	0.05236		655.3	
31	0.05058	0.05095	613.2	629.2
31.5	0.04849	0.04898	566.5	583.8
32	0.04592	0.04661	509.2	530.4
32.25	0.04433		470.5	
32.5		0.04353		490.2

Velocity of Sound in Liquid Parahydrogen

T = 15.000 °K		T = 17.000 °K		T = 19.000 °K		T = 20.500 °K	
P atm	Velocity of Sound m/sec	P atm	Velocity of Sound m/sec	P atm	Velocity of Sound m/sec	P atm	Velocity of Sound m/sec
34.52	1351.6	81.36	1458.3	174.39	1648.3	229.88	1739.8
22.01	1311.4	51.[illegible]	1375.3	135.67	1567.2	195.49	1676.7
8.81	1265.3	30.15	1306.3	99.56	1481.6	150.62	1585.5
		[illegible].04	1215.8	73.99	1413.0	124.12	1525.3
				44.23	1321.1	91.73	1442.8
				40.72	1309.7	63.51	1360.2
				22.94	1243.4		


DIFFERENCE IN VELOCITY OF SOUND BETWEEN SATURATED LIQUID NORMAL AND PARA HYDROGEN
(Younglove, 1965)
VELOCITY OF SOUND DIFFERENCE $C_n - C_p$, m/sec
20
15
10
15
20
25
30
TEMPERATURE, °K

3.6 P-V-T AND VIRIAL COEFFICIENT DATA

Data Sources:

Long, E. A., and Brown, O. L. I. (1937), A Comparison of the Data of State of Normal and Para Hydrogen from the Boiling Point to 55°K, J. Am. Chem. Soc. 59, 1922-24.

Beenakker, J. J. M., Varekamp, F. H., and Knaap, H. F. P. (1960), The Second Virial Coefficient of Ortho and Para Hydrogen at Liquid Hydrogen Temperatures, Physica 26, 43-51.

Goodwin, R. D. (1961), Apparatus for Determination of Pressure-Density-Temperature Relations and Specific Heats of Hydrogen to 350 Atmospheres at Temperatures above 14°K, J. Res. Natl. Bur. Std. 65c, 231-43.

Goodwin, R. D., Diller, D. E., Roder, H. M., and Weber, L. A. (1963), Pressure-Density-Temperature Relations of Fluid Para Hydrogen from 15 to 100°K at Pressures to 350 Atmospheres, J. Res. Natl. Bur. Std. 67a, 173-92.

Comments:

The difference in the P-V-T surfaces of ortho and para hydrogen are very small. Thus only measurements of high accuracy or direct difference measurements are useful to predict these differences. Most of the published experimental P-V-T data have been omitted from this tabulation because the systematic errors appear to be at least as large as the ortho-para differences. These data will be examined in a continuation of this study of ortho-para hydrogen properties in an attempt to determine the actual differences, or at least to establish an upper limit for the ortho-para differences. The following extensive data sources have been omitted from this tabulation:

(1) Johnston, H. L., et al. (1953), Ohio State University, Cryogenics Laboratory Tech. Rept. No. TR 264-25.

(2) Johnston, H. L., et al. (1954), J. Am. Chem. Soc. 76, 1482-86.

(3) Michels, A., et al. (1959), Physica 25, 25-42.

Long and Brown (1937) determined the second virial coefficients of normal and para hydrogen with a constant volume gas thermometer from 20 to 56°K. They concluded that there is no essential difference in the second virial coefficients of the two forms of hydrogen.

Beenakker, et al. (1960) measured the difference between the second virial coefficients of normal and para hydrogen. They reported differences of about 1% at 20.5 and 18.3 °K with a sensitivity of the order of 3×10^{-6} amagat. Their results indicate that the difference in second virial coefficient is a linear function of composition.

Goodwin (1961) measured seven P-V-T state points of normal hydrogen as a check of his apparatus which was used for extensive measurements of parahydrogen density. The parahydrogen data included below for comparison were linearly interpolated from the values reported by Goodwin, et al. (1963). The parahydrogen data extend from 15 to 100°K and to pressures up to 350 atmospheres. These para and normal hydrogen P-V-T data are comparable because of their high precision, and the probability that any systematic errors in the two sets are essentially the same, since these measurements are made from the same apparatus and by the same experimenters. These data have a reported accuracy and precision of 0.1 and 0.02%, respectively. (The NBS-1955 Temperature Scale was used.)

Long and Brown (1937)			
Second Virial Coefficient, B, in Amagat Units as Defined by $PV_A = A + B/V_A$ where $V_A = V/V_o$ and V_o = Volume at 0°C and 1 Atm			
T, °K	Second Virial Coefficient		
	Normal	Para	Difference
20.87	-465×10^{-6}	-473×10^{-6}	-8×10^{-6}
24.11	-434	-435	-1
27.65	-407	-407	0
32.43	-371	-377	-6
37.08	-339	-343	-4
41.49		-316	
41.64	-310	-315	-5
43.95		-301	
46.45	-282		
48.45		-265	
52.51		-235	
56.21		-216	

Beenakker, et al. (1960)	
Second Virial Coefficient, B, in Amagat Units as Defined by $PV_A = A(1 + B/V_A)$	
T, °K	Difference Para-Normal
20.5	64×10^{-6}
20.5	65
20.5	68
20.5	64
20.5	68
20.5	71
20.5	66
20.5	72
20.5	69
20.5	67
18.3	95
18.3	115
18.3	75

Goodwin, et al. (1961) and (1963)				
Pressure-Volume-Temperature Data (NBS-1955 Temperature Scale)				
T, °K	P, atm	Volume, cm^3/mole		
		Normal	Para	Difference
28	30.869	30.52	30.63	0.11
30	45.357	30.54	30.63	0.09
32	59.738	30.56	30.64	0.08
36	88.443	30.59	30.65	0.06
40	116.969	30.62	30.68	0.06
45	151.884	30.65	30.69	0.04
50	186.213	30.69	30.70	0.01

3.7 SATURATION DENSITIES

Data Sources:

Scott, R. B., and Brickwedde, F. G. (1937), The Molecular Volumes and Expansivities of Liquid Normal Hydrogen and Parahydrogen, J. Chem. Phys. 5, 736-44.

Goodwin, R. D., Diller, D. E., Roder, H. M., and Weber, L. A. (1961), The Densities of Saturated Liquid Hydrogen, Cryogenics 2, 81-83.

Knaap, H. F. P., Knoester, M., and Beenakker, J. J. M. (1961), The Volume Change on Mixing for Several Liquid Systems and the Difference in Molar Volume between the Ortho and Para Modifications of the Hydrogenic Molecules, Physica 27, 309-18.

Comments:

The saturation density differences in ortho and para hydrogen are small (about 0.5%), therefore only measurements of high accuracy or direct measurements of differences are reviewed here. Further analysis will be required to determine if their selection has been prudent.

The effect on density of the change in vapor pressure between ortho and para hydrogen has been examined. The change in liquid density corresponding to the observed difference in vapor pressure is less than 0.01% except within 2°K of critical temperature. Thus the differences in liquid saturation densities of ortho and para hydrogen are indicative of the differences in the P-V-T surfaces of ortho and para hydrogen near the saturated liquid line. However, the effect of the vapor pressure differences on the saturated vapor densities is as much as 6% near the triple point and decreases to less than 1% at 30°K. The differences in ortho-para saturation densities are thus not indicative of the differences in ortho-para P-V-T surfaces near the saturated vapor line.

Scott and Brickwedde (1937) measured the densities of saturated liquid normal and para hydrogen with a fused quartz dilatometer at temperatures from 14 to 20.4°K. The amount of hydrogen was determined from the pressure of the gas after expansion into a calibrated flask at a measured temperature. Their data is represented to within its precision by the equations

$$V(n\text{-}H_2)\ cm^3/mole = 24.747 - 0.08005\ T + 0.012716\ T^2$$

$$V(p\text{-}H_2)\ cm^3/mole = 24.902 - 0.0888\ T + 0.013104\ T^2.$$

They measured the vapor pressure and calculated temperature from a vapor pressure equation, therefore their temperatures are not tabulated here. These authors indicate a probable error of 0.03% in their experimental volumes.

Goodwin, et al. (1961) presents a comparison (using the NBS-1955 Temperature Scale) of the available saturated density data for liquid para and normal hydrogen. The normal hydrogen data are taken from Scott and Brickwedde (1937) and the parahydrogen data were measured by Goodwin, et al. (1961). These density determinations were reported to have a precision of two parts in 10,000 and an accuracy of 10 parts in 10,000.

Knaap, et al. (1961) determined the volume change on mixing of normal and para hydrogen for compositions ranging from 0.27 to 0.70 mole fraction normal hydrogen at 20.4°K. The accuracy is claimed to be of the order of 5 mm^3/mole.

Scott and Brickwedde (1937)

Saturated Liquid Normal Hydrogen

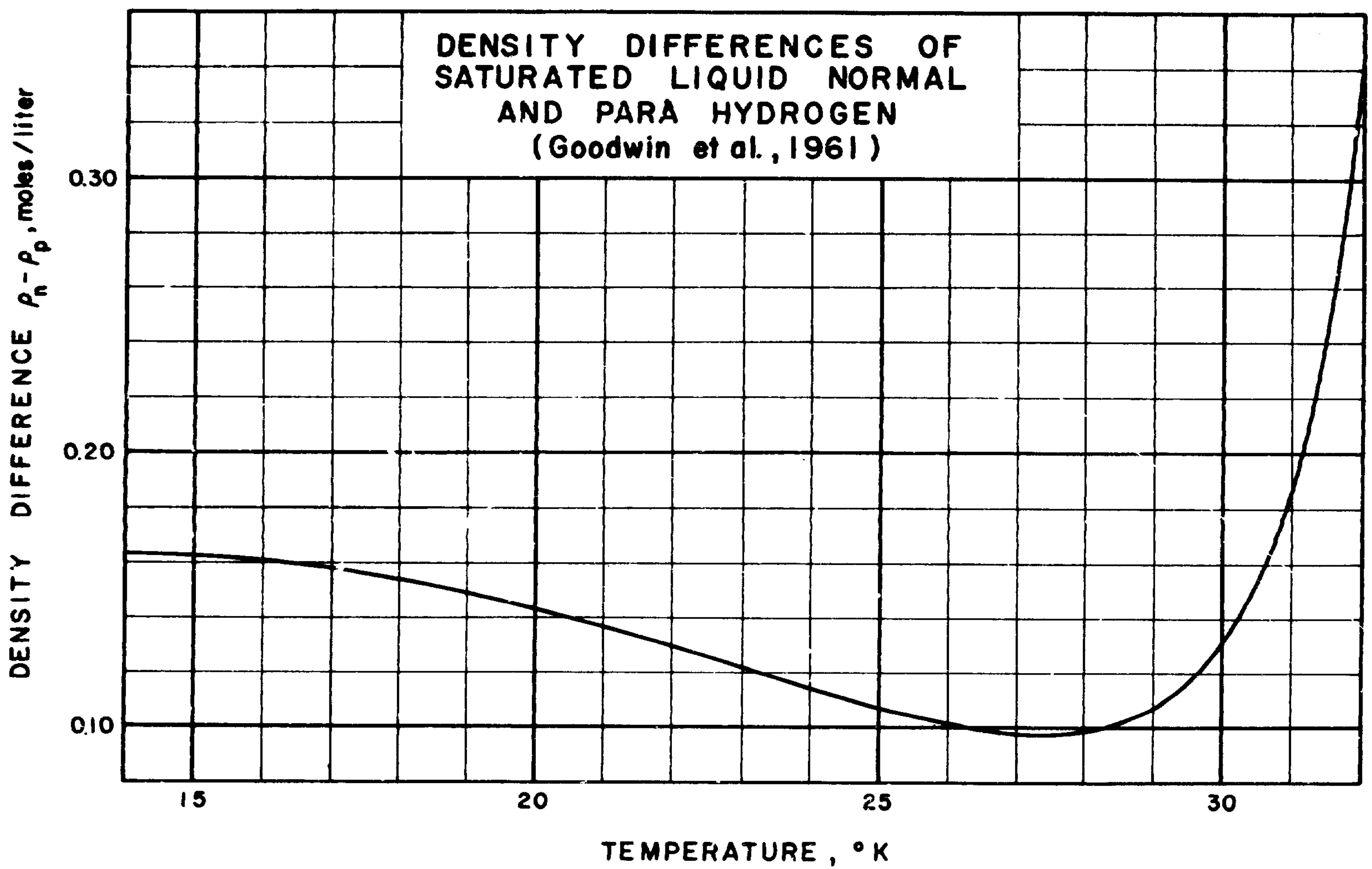
Vapor Pressure mm Hg	Volume cm^3/mole
749.8	28.395
65.0	26.179
754.1	28.386
65.4	26.207
220.0	27.000
335.3	27.383
518.8	27.870
751.4	28.390
752.4	28.389
81.7	26.313
108.7	26.488
201.8	26.930
308.9	27.308
410.2	27.594
571.8	28.009
751.7	28.387
758.7	28.383
79.5	26.284
111.2	26.492
186.7	26.862
290.7	27.239
450.6	27.696
550.9	27.943
756.9	28.382

Saturated Liquid Parahydrogen

Vapor Pressure mm Hg	Volume cm^3/mole
68.5	26.330
117.9	26.649
221.8	27.121
374.0	27.625
633.7	28.267
754.2	28.529
140.5	26.753
314.7	27.449
567.8	28.121
748.3	28.514

Goodwin, et al. (1961)			
Saturated Liquid (NBS-1955 Temperature Scale)			
T, °K	Density (moles/liter)		
	Para	Normal	Difference
13.803	38.1998		
13.947		38.3038	
14	38.1191	38.2819	0.1628
15	37.6987	37.8609	0.1622
16	37.2586	37.4190	0.1604
17	36.7970	36.9546	0.1576
18	36.3119	36.4656	0.1537
19	35.8010	35.9498	0.1488
20	35.2615	35.4045	0.1430
20.268	35.1115		
20.380		35.1889	
21	34.6898	34.8263	0.1365
22	34.0821	34.2114	0.1293
23	33.4330	33.5549	0.1219
24	32.7363	32.8506	0.1143
25	31.9835	32.0908	0.1073
26	31.1635	31.2650	0.1015
27	30.2610	30.3590	0.0980
28	29.2534	29.3522	0.0988
29	28.1060	28.2131	0.1071
30	26.7588	26.8889	0.1301
31	25.0921	25.2776	0.1855
32	22.7821	23.1238	0.3417
32.984	15.2672		
33.		19.0252	
33.180		14.9365	

Knaap, et al. (1961)	
Mole fraction of $n\text{-}H_2$	Volume change on mixing for mixtures of $n\text{-}H_2$ and $p\text{-}H_2$ at 20.4°K cm^3/mole
0.27	0.017
0.28	0.014
0.44	0.016
0.50	0.018
0.70	0.010
0.70	0.011



DENSITY DIFFERENCES OF SATURATED LIQUID NORMAL AND PARA HYDROGEN (Goodwin et al., 1961)
0.30
0.20
0.10
DENSITY DIFFERENCE $\rho_n - \rho_p$, moles/liter
15
20
25
30
TEMPERATURE, °K

3.8 VAPOR PRESSURE

Data Sources:

Woolley, H. W., Scott, R. B., and Brickwedde, F. G. (1948), Compilation of Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modifications, J. Res. Natl. Bur. Std. 41, 379-475, RP-1932.

White, D., Friedman, A. S., and Johnston, H. L. (1950), The Vapor Pressure of Normal Hydrogen from the Boiling Point to the Critical Point, J. Am. Chem. Soc. 72, 3927-30.

Hoge, H. J., and Arnold, R. D. (1951), Vapor Pressures of Hydrogen, Deuterium, and Hydrogen Deuteride and Dew-Point Pressures of their Mixtures, J. Res. Natl. Bur. Std. 47, 63-74.

Grilly, E. R. (1951), The Vapor Pressures of Hydrogen, Deuterium and Tritium up to Three Atmospheres, J. Am. Chem. Soc. 73, 843-46.

Weber, L. A., Diller, D. E., Roder, H. M., and Goodwin, R. D. (1962), The Vapor Pressure of 20°K Equilibrium Hydrogen, Cryogenics 2, 236-38.

Barber, C. R., and Horsford, A. (1963), The Determination of the Boiling and Triple Points of Equilibrium Hydrogen and its Vapor Pressure-Temperature Relation, Brit. J. Appl. Phys. 14, 920-23.

Van Itterbeek, A., Verbeke, O., Theewes, F., Staes, K., and De Boelpaep, J. (1964), The Difference in Vapor Pressure between Normal and Equilibrium Hydrogen. Vapor Pressure of Normal Hydrogen between 20°K and 32°K, Physica 30, No. 6, 1238-44.

Comments:

Vapor pressure data published prior to the research paper by Woolley, et al. (1948) were not considered in this report. The earlier values are assumed to be well represented by the results of Woolley, et al. Vapor pressure differences calculated from the equations presented by Woolley, et al. (1948) agree well with more recent data although the vapor pressures themselves above 20°K are not in good agreement with recent data. Hoge and Arnold (1951) suggest that Brickwedde and Scott (unpublished data cited by Woolley, et al. 1948) actually measured these differences rather than the vapor pressures. The vapor pressure differences of Woolley, et al. (1948) and the measured values of Van Itterbeek are illustrated graphically. To obtain best values of the differences in the vapor pressure of normal and para hydrogen, in a continuation of this study, the vapor pressure data from the other sources listed here will be corrected for temperature scale and interpolated. No attempt has been made to include isolated vapor pressure values such as normal boiling point and triple point determinations; only measurements over extended temperature ranges are included. The reader is cautioned that best values of vapor pressure are not indicated; the differences in ortho and para vapor pressures are of primary interest here.

Woolley, et al. (1948) examined the experimental vapor pressure data and selected the unpublished data of Brickwedde and Scott. The NBS-1939 Temperature Scale was used.

White, et al. (1950) measured the vapor pressure of normal hydrogen from 21 to 33°K. White, et al. indicated an accuracy of 0.02°K, and 0.03 mm of Hg below 2.5 atmospheres and one part in 30,000 above 2.5 atmospheres. The temperature scale used is not reported.

Hoge and Arnold (1951) measured the vapor pressure of equilibrium (20.4°K) hydrogen at temperatures from 17°K to 33°K. These data are based on the NBS-1939 Low Temperature Scale (below 90°K). They point out here that the results of Brickwedde and Scott, unpublished but cited in Woolley, et al. (1948), differ systematically from their results because of temperature scale differences. Most of the data of Brickwedde and Scott were taken before the NBS-1939 scale was established. It is also indicated that the Brickwedde and Scott data are based on equilibrium hydrogen data and differences of vapor pressures of the various modifications of hydrogen.

Grilly (1951) measured the vapor pressure of normal hydrogen from 14 to 24.5°K. The data from 14 to 20°K are well represented by the Brickwedde and Scott equation but above 20°K a different equation was required. The NBS-1939 Temperature Scale was used. The estimated average uncertainty is 0.1% in pressure or 0.004°K in temperature.

Weber, et al. (1962) measured the vapor pressure of 20°K equilibrium hydrogen at temperatures from 20 to 33°K. The NBS-1955 Temperature Scale was used. An uncertainty of ±0.003 atm is indicated.

Barber and Horsford (1963) report vapor pressure values for equilibrium hydrogen for temperatures from 13.8 to 20.2°K. The NPL (National Physical Laboratory) Temperature Scale with an ice point of 273.15°K and an oxygen point of 90.177°K is used.

Van Itterbeek, et al. (1964) measured the difference in vapor pressure of normal and para hydrogen and the vapor pressure of normal hydrogen, simultaneously. The normal boiling points of normal and para hydrogen were determined to 20.389 and 20.269°K, respectively. The results were reported as accurate to within ±0.004 kg/cm². The vapor pressure differences of the Brickwedde and Scott equations are illustrated graphically by Van Itterbeek, et al. to 31°K and appear in good agreement with these data.

Woolley, et al. (1948)			
(NBS-1939 Temperature Scale)			
T, °K	Vapor Pressure (mm of Hg)		
	Normal	Para	Difference
13.813		52.8	
13.957	54.0	57.4	3.4
14	55.4	58.8	4.4
15	95.0	100.4	5.4
16	153.3	161.2	7.9
17	235.2	246.2	11.0
18	345.9	360.6	14.7
19	490.8	510.1	19.3
20	675.7	700.3	24.6
20.273	733.9	760.0	26.1
20.390	760.0	786.8	26.8
21	906.4	937.0	30.6
22	1189.0	1226.6	37.6
23	1529.6	1574.9	45.3

White, et al. (1950)	
Vapor Pressure of Normal Hydrogen	
Temp. °K	Vapor Pressure atm.
27.31	4.8956
28.85	6.4144
32.00	10.6090
20.70	1.1596
21.81	1.4844
22.65	1.8155
23.72	2.3493
24.73	2 9510
25.70	3.6126
26.74	4.4178
28.20	5.7618
29.56	7.2763
30.19	8.0645
30.79	8.8359
31.40	9.6981
32.36	11.2065
33.07	12.3553
33.140	12.620
33.244	12.797

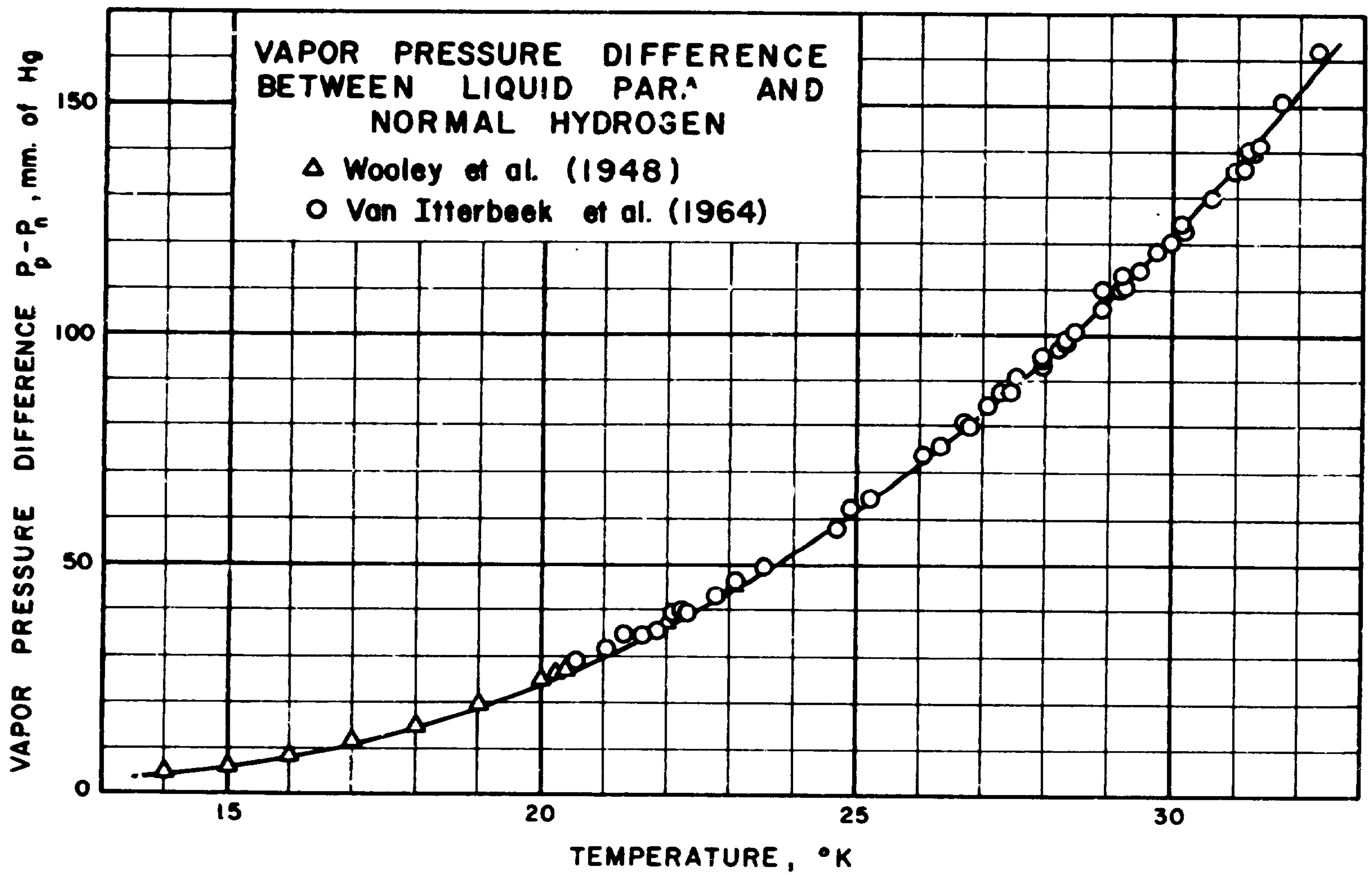
Hoge and Arnold (1951)			
Vapor Pressure of 20.4°K Equilibrium Hydrogen			
Temp. °K	Vapor Pressure mm Hg	Temp. °K	Vapor Pressure mm Hg
17.8294	338.4	31.4021	7660.2
18.5812	442.1	16.9752	243.1
19.1245	530.7	15.8414	149.7
20.0[illegible]1	707.7	22.2604	1308.4
20.4069	789.6	22.9058	1534.9
20.5118	813.7	25.0473	2488.5
16.9549	241.4	27.8744	4299.6
20.2648	757.1	29.9173	6080.2
20.5167	815.2	30.9020	7102.8
20.8655	900.7	31.8910	8255.1
21.2046	989.8	22.2800	1313.8
20.9513	922.1	22.5792	1416.1
21.3379	1026.8	28.8797	5121.5
23.6441	1827.1	31.0820	7302.5
24.4501	2189.4	20.9534	922.5
24.9003	2414.1	21.6873	1127.2
25.5711	2773.5	25.8955	2960.3
26.1980	3142.6	32.8933	9566.2
26.7811	3517.5	32.8936	9564.4
27.4083	3952.7	32.8926	9559.3
28.3858	4705.7	32.6457	9219.5
29.3956	5583.9	32.3853	8875.1
30.3776	6544.6	32.1392	8557.7

Grilly (1951)	
Vapor Pressure of Liquid Normal Hydrogen	
Temp. °K	Vapor Pressure mm Hg
19.560	587.8
20.092	694.7
21.323	986.6
22.047	1196.8
22.803	1445.9
23.412	1675.0
23.941	1897.4
24.445	2125.7
24.445	2125.7

Weber, et al. (1962)			
Vapor Pressure of Parahydrogen			
Temp. °K	Vapor Pressure atm.	Temp. °K	Vapor Pressure atm.
20.268	1.0000	31.500	10.2539
22.000	1.6124	32.000	11.0502
23.000	2.0688	32.000	11.0516
25.000	3.2462	32.000	11.0522
26.000	3.9826	32.500	11.8988
27.000	4.8285	32.500	11.8976
28.000	5.7920	32.500	11.8989
29.000	6.8863	32.600	12.0749
30.000	8.1162	32.600	12.0742
30.000	8.1169	32.600	12.0751
30.000	8.1171	32.700	12.2526
30.500	8.7873	32.700	12.2520
30.500	8.7885	32.700	12.2536
30.500	8.7886	32.800	12.4326
31.000	9.5023	32.800	12.4330
31.000	9.5029	32.800	12.4352
31.000	9.5005	32.900	12.6168
31.000	9.5003	32.900	12.6187
31.500	10.2525	32.900	12.6183
31.500	10.2535	33.000	12.8043

Barber and Horsford (1963)	
Equilibrium Hydrogen (NPL Temperature Scale)	
Temp. °K	Vapor Pressure mm Hg
20.2705	760.0
19.0503	519.527
18.4474	423.277
17.4286	291.293
16.2885	183.031
15.3485	119.379
15.0053	100.845
14.5236	78.618
13.9768	58.278
13.8157	52.948

Van Itterbeek, et al. (1964)		
(NPL Temperature Scale)		
T, °K	Vapor Pressure, kg/cm²	
	Normal	Difference Para-Normal
20.555		3.89×10^{-2}
20.560		3.89
21.023	1.236	4.30
21.298	1.334	4.71
21.607	1.452	4.72
21.835	1.546	4.86
22.069	1.635	5.30
22.242	1.715	5.40
22.331		5.35
22.772	1.965	5.85
23.085	2.117	6.30
23.537	2.355	6.67
24.680	3.051	7.84
24.929	3.221	8.45
25.209	3.418	8.73
26.025		10.03
26.323	4.280	10.29
26.721	4.624	11.00
26.791	4.704	10.60
27.072	4.940	11.54
27.256	5.121	11.89
27.479	5.343	11.91
27.540	5.382	12.40
27.964	5.829	12.71
27.964		12.92
27.970	5.837	12.99
28.201		13.20
28.289	6.189	13.39
28.301	6.186	13.47
28.464	6.366	13.71
28.888	6.842	14.83
28.888		14.38
29.178	7.195	14.98
29.207	7.223	15.39
29.238	7.264	15.03
29.500	7.586	15.52
29.771	7.932	16.06
29.979	8.236	16.38
29.996	8.224	
30.137	8.452	16.88
30.172	8.476	16.71
30.601	9.086	17.64
30.971	9.604	18.46
31.119	9.817	18.57
31.146	9.864	19.07
31.238	10.011	19.02
31.352	10.172	19.23
31.720	10.758	20.52
32.276	11.679	22.05


VAPOR PRESSURE DIFFERENCE BETWEEN LIQUID PARA AND NORMAL HYDROGEN
Δ Wooley et al. (1948)
O Van Itterbeek et al. (1964)
VAPOR PRESSURE DIFFERENCE $P_p - P_n$, mm. of Hg
0
50
100
150
15
20
25
30
TEMPERATURE, °K

3.9 LATENT HEAT OF VAPORIZATION

Data Sources:

Woolley, H. W., Scott, R. B., and Brickwedde, F. G. (1948), Compilation of Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modification, J. Res. Natl. Bur. Std. 41, 379-475, RP-1932.

Goodwin, R. D., Diller, D. E., Roder, H. M., and Weber, L. A. (1961), The Densities of Saturated Liquid Hydrogen, Cryogenics 2, 81-83.

Roder, H. M., Diller, D. E., Weber, L. A., and Goodwin, R. D. (1963), The Orthobaric Densities of Parahydrogen, Derived Heats of Vaporization and Critical Constants, Cryogenics 3, 16-22.

Goodwin, R. D., Diller, D. E., Roder, H. M., and Weber, L. A. (1964), Second and Third Virial Coefficients for Hydrogen, J. Res. Natl. Bur. Std. 68a, 121.

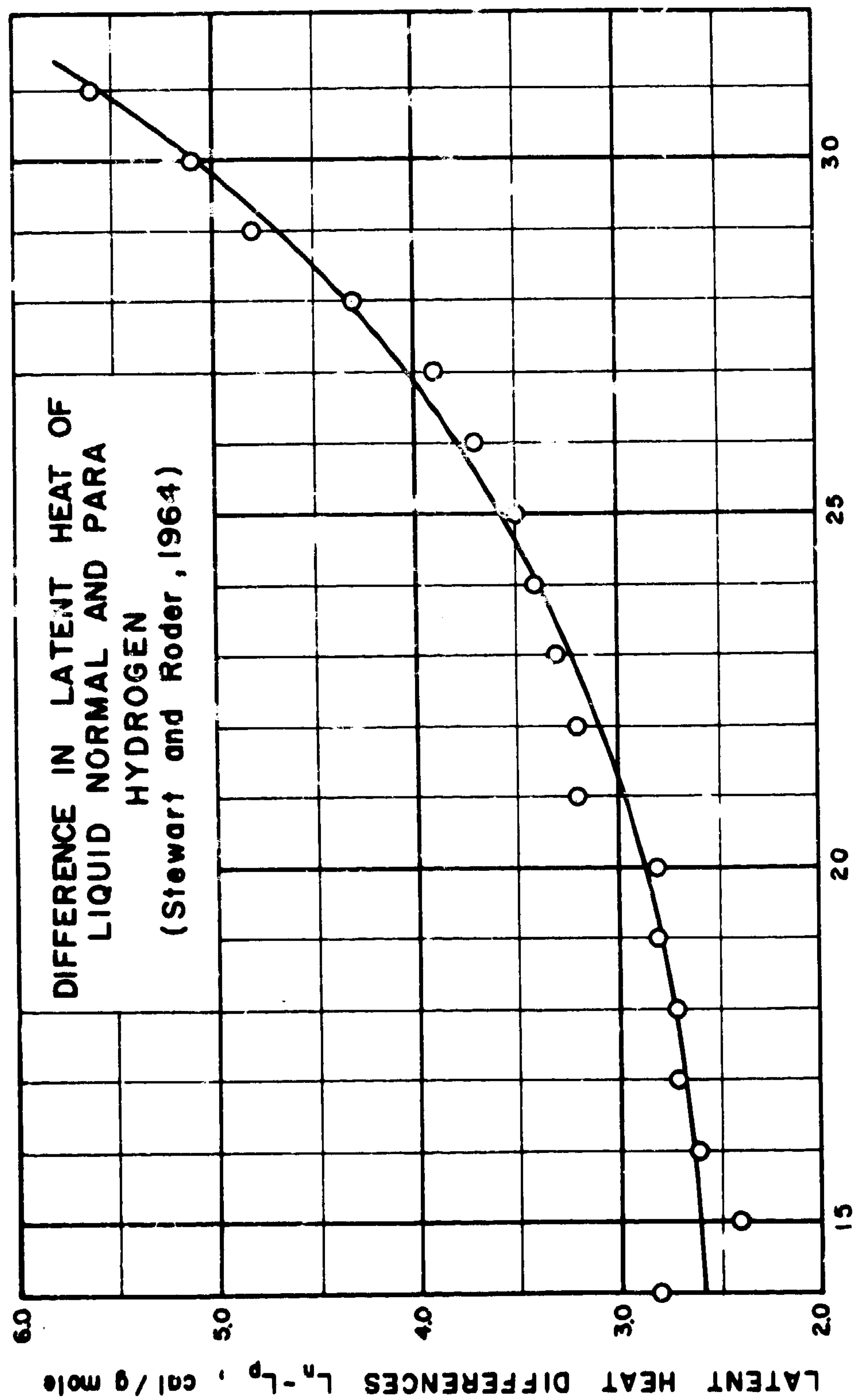
Stewart, R. B., and Roder, H. M. (1964), Chapter 11, Properties of Normal and Para Hydrogen, p. 379-404 in Technology and Uses of Liquid Hydrogen, Pergamon Press, New York.

Comments:

The values for the latent heat of vaporization of para hydrogen are from Roder, et al. (1963).

The latent heat of vaporization of normal hydrogen was calculated from data compiled by Stewart and Roder (1964) from the Clausius-Clapeyron equation. The original data are as follows from the following sources. The saturated liquid densities were obtained from Goodwin, et al. (1961). The saturated vapor densities were calculated by Stewart and Roder using the para hydrogen virial coefficients by Goodwin, et al. (1964) under the assumption that the virial coefficients of normal and para hydrogen differ only slightly. The vapor pressure values and slopes were from the equation given by Woolley, et al. (1948).

Stewart and Roder (1964)			
T, °K	Latent Heat of Vaporization, cal/g mole		
	Normal	Para	Difference
14	219.9	217.1	2.8
15	220.7	218.3	2.4
16	221.1	218.5	2.6
17	221.1	218.4	2.7
18	220.6	217.9	2.7
19	219.6	216.8	2.8
20	218.0	215.2	2.8
21	215.7	212.5	3.2
22	212.7	209.5	3.2
23	208.9	205.6	3.3
24	204.2	200.8	3.4
25	198.5	195.0	3.5
26	191.5	187.8	3.7
27	183.1	179.2	3.9
28	173.0	168.7	4.3
29	160.6	155.8	4.8
30	145.2	140.1	5.1
31	125.4	119.8	5.6
32		90.8	



DIFFERENCE IN LATENT HEAT OF LIQUID NORMAL AND PARA HYDROGEN
(Stewart and Roder, 1964)
LATENT HEAT DIFFERENCES $L_n - L_p$, cal / g mole
6.0
5.0
4.0
3.0
2.0
TEMPERATURE, °K
15
20
25
30